UNIVERSITY OF CALIFORNIA,
IRVINE

Weather Augmented Risk Determination (WARD) System

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Civil and Environmental Engineering

by

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2015

DEDICATION

To:

My beautiful wife and daughter

"Keep your dreams alive. Understand to achieve anything requires faith and belief in yourself, vision, hard work, determination, and dedication. Remember all things are possible for those who believe."
- Gail Devers

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my advisor, Dr. Amir AghaKouchak for all his excellent guidance, caring, patience and support throughout my Master's Thesis. Dr. AghaKouchak has been a great influence, leader, supporter, and role model. I am forever grateful for his guidance throughout my Master's degree. I would also like to thank my committee members Dr. Gao and Dr. Kuo-Lin Hsu. Dr. Gao was a great professor and I learned much in his class. I would like to thank Dr. Kuo-Lin Hsu for accepting to put his time to be a part of my thesis committee. I would also like to thank my parents for their continuing love and support throughout my education.

I would like to thank Omid Mazdiyasni, who as a good friend, and is always willing to help and give his best suggestions. Finally, I would like to acknowledge Farshad Momtaz who contributed in developing the interface of the software developed in this thesis.

ABSTRACT OF THE THESIS

Weather Augmented Risk Determination (WARD) System
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University of California, Irvine, 2015

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Extreme climatic events have direct (e.g., physical damage) and indirect impacts (e.g., low air quality caused by a dry spell) on society, economy and the environment. Based on the United States Bureau of Economic Analysis (BEA) data, over one third of the U.S. GDP can be considered as weather-sensitive involving some degree of weather risk. This expands from a local scale concrete foundation construction to large scale transportation systems. Extreme and unexpected weather conditions have always been considered as one of the probable risks to human health, productivity and activities. The construction industry is a large sector of the economy, and is also greatly influenced by weather-related risks including work stoppage and low labor productivity. Identification and quantification of these risks, and providing mitigation of their effects are always the concerns of construction project managers. In addition to severe weather conditions' destructive effects, seasonal changes in weather conditions can also have negative impacts on human health. Work stoppage and reduced labor productivity can be caused by precipitation, wind, temperature, relative humidity and other weather conditions. Historical and project-specific weather information can improve better project management and mitigation

planning, and ultimately reduce the risk of weather-related conditions. This thesis proposes new software for project-specific user-defined data analysis that offers (a) probability of work stoppage and the estimated project length considering weather conditions; (b) information on reduced labor productivity and its impacts on project duration; and (c) probabilistic information on the project timeline based on both weather-related work stoppage and labor productivity. The software (WARD System) is designed such that it can be integrated into the already available project management tools. While the system and presented application focuses on the construction industry, the developed software is general and can be used for any application that involves labor productivity (e.g., farming) and work stoppage due to weather conditions (e.g., transportation, agriculture industry). The system is designed to offer work stoppage and labor productivity information based on user-defined weather conditions.

Chapter 1: Introduction

Weather conditions and climate extremes affect all living beings in one way or another. Whether it is high temperatures, low precipitation, flooding, high winds, hurricanes, or any number of extreme events, weather affects our livelihood and daily life. Extreme climatic events especially have great effects on human health and the economy. Weather events in the United States such as rain and cooler than average days can add up, and have an economic effect of up to $485 billion per year [Lazo et al., 2011]. El Nino events can cause coastal storms, heavy rains, flooding, landslides, and damage to agricultural industries in California. The 1997/1998 El Nino event caused losses totaling over $1.4 billion in California alone, and $5.4 billion across the nation [Changnon, 2000]. Also, droughts cause approximately $7 billion per year in damages globally [Mazdiyasni and AghaKouchak, 2015, Hao and AghaKouchak, 2013, Mehran et al., 2015]. Floods cause great damage, resulting in loss of life, loss of property, and huge economic losses. From 1955 to 2008, floods in the United States caused $397 billion in damages [National Center for Atmospheric Research, 2011, Nguyen et al., 2015;]. Decision makers need to make informed decisions, taking into account all variables to prevent great economic losses.

Weather directly or indirectly affects decision making in every United States economic sector [Lazo et al., 2011]. For example, the US agricultural sector lost almost $3 billion during the 1997/1998 El Nino event and the 1998/1999 La Nina event [Adams et al., 1999]. The four-year long and still ongoing California drought [AghaKouchak et al., 2015], compounded by extreme temperatures [Shukla et al., 2015; AghaKouchak et al., 2014] have also resulted in significant local impacts on different sectors especially on the agriculture and labor market [Howitt et al. 2015]. Also, the transportation industry experienced 24.7 million minutes in flight delays

[Bureau of Transportation Statistics, 2011]. High temperatures lead to increased power demand, and cause power transmission problems. One degree change in summer months can result in millions of dollars in additional electricity generation [Altalo and Hale, 2004,]. One very important sector that is greatly affected by weather is the construction industry. Not only do severe weather conditions have negative impacts on scheduling and economic damage in the construction industry, seasonal changes in weather conditions such as precipitation, temperature, and wind can also have impacts on labor productivity and health of the workforce.

The construction industry contributes to a large portion of the overall economy in the United States [Finkel, 2015]. In 1997, construction projects accounted for approximately ten percent of the gross domestic product in the United States. Also, over ten million people are employed in the US construction industry, making it the largest manufacturing industry in the United States [Allmon et al., 2000].

Construction projects can be delayed due to numerous factors including contractor management, material management practices, disruptions during work, changes in the project, and unfavorable weather conditions [Randolph et al., 1999]. Since construction projects are generally executed in an outdoor environment, weather conditions greatly affect project progression. Weather impacts are reported to be one of the biggest factors that cause cost overruns and delays in construction projects [Moselhi et al., 1997; Badlwin et al., 1971; Koehn and Meilhede, 1989; Laufer and Cohenca, 1990]. Approximately half of all construction activities are sensitive to weather conditions [Benjamin et al., 1973]. There are different ways weather conditions can cause delays in construction projects [Smith et al., 1989]; weather conditions can cause a reduction in labor productivity or cause complete work stoppage [Moselhi et al., 1997]. Complete work stoppage can be caused by the inability of construction workers to continue working due to severe weather conditions such as heavy precipitation, snow, or high speed winds. Work stoppage can also be due to compliance with safety regulations [Moselhi et al., 1997].

Labor productivity is another way weather conditions affect construction schedules and timelines. Labor productivity is considered one of the best indicators for efficiency during construction projects. High efficiency during construction leads to high profitability throughout the project [Rojas and Aramvareekul, 2003]. Also, due to the size of the construction industry, changes in productivity have significant direct effects on the national economic wellbeing in the United States [Allmon et al., 2000]. Labor productivity drivers include weather conditions, coordination of subcontractors and contractors, material management and accurate scheduling [Rojas and Aramvareekul, 2003]. Focusing on the effects of weather conditions on labor productivity, findings suggest that work performance decreases at temperatures above 80 degrees Fahrenheit and below 40 degrees Fahrenheit. Furthermore, relative humidity below 80% is necessary for higher work efficiency. As temperatures rise above 80 degrees, relative humidity becomes an important factor in work efficiency [Hanna, 2004].

A system that can take advantage of climatological information can be useful for long term planning and bidding in construction projects. An accurate indication of average number of lost days due to weather conditions can improve scheduling and competitive bidding. It can help contractors in planning for overtime requirements and potential economic losses [Cantwell, 1987]. Precise labor productivity assessments can also assist in providing more reliable scheduling, which in turn result in greater profitability [Rojas and Aramvareekul, 2003]. Providing a comprehensive estimate of weather impacts (including reduced labor productivity and interruptions that cause work stoppage) can facilitate the preparation of realistic schedules, cost estimates, and reliable bids [Moselhi et al., 1997]. Severe weather conditions can cause damage to projects in progress, resulting in reconstruction of those parts of the project. This leads to loss of material, lost labor, and delays in projects, having detrimental economic effects. However, weather conditions that do not directly cause damage to projects also result in great economic losses by causing work stoppage and reduced labor productivity.

This paper proposes new software for project-specific user-defined data analysis that uses historical data (more than 35 years) to account for (a) probability of work stoppage and the estimated project length considering weather conditions; (b) information on reduced labor productivity and its impacts on project duration; and (c) probabilistic information on project timeline based on both weather-related work stoppage and labor productivity. The software (WARD System) is designed such that it can be integrated into the already available project management tools.

While the system and presented application focuses on the construction industry, the developed software is general and can be used for any application that involves labor productivity (e.g., farming) and work stoppage due to weather conditions (e.g., transportation, agriculture industry). The system is designed such that it offers work stoppage and labor productivity information based on user-defined weather conditions.

Chapter 2: Data

The weather data sets this software uses is from the North American Land Data Assimilation Systems (NLDAS) [Maurer et al., 2002][Livneh et al., 2013] which has been used in a wide variety of studies [e.g., Mazdiyasni and AghaKouchak, 2015, Hao et al., 2014; Shukla et al., 2015]. In the current version of the model, the climate variables used include:

- Precipitation,
- temperature,
- specific humidity,
- relative humidity,
- pressure,
- wind,
- solar radiation,
- Soil moisture.

Precipitation, temperature, specific humidity, pressure, wind and solar radiation are from the observation-based forcings [Maurer et al., 2002; Livneh et al., 2015]. Soil moisture is from Noah LSM Model [Wood et al., 1997; Liang et al., 1996] and relative humidity is calculated using specific humidity and pressure using as:

$$RH = 0.263pq\left[exp\left(\frac{17.67(T - T_0)}{T - 29.65}\right)\right]^{-1}$$

q : specific humidity or the mass mixing ratio of water vapor to total air (dimensionless)

p : pressure (Pa)

T : temperature (K)

T0 : reference temperature (typically 273.16 K) (K)

These data sets have 0.125° spatial and hourly temporal resolutions. The data record covers 1980-present. The data can be access from:

http://disc.sci.gsfc.nasa.gov

Chapter 3: Method

The user inputs the project information such as project location, project and task dates, and project constraints. Project constraints include thresholds to which each task is sensitive. Example constraints include:

- working days,
- working hours per shift,
- number of shifts during each day, and
- holidays.

Additional constraints can be added depending on the type of the project and safety compliance issues. Using the selected constraints, the program extracts the necessary data from the database. The program then calculates the probabilities of work stoppage for each hour using historical weather data and creates a cumulative distribution function (i.e., identifies the risk of work stoppage based on climatology in the location of interest). The probability of stoppage is estimated by counting the number of times the variable goes above or below a user defined threshold (e.g., hourly temperatures exceeding 110 ^{o}F). This analysis is based on the cumulative distribution function (CDF) of the variable of interest:

$$F(x) = P(X \leq x)$$

which gives probabilities of passing the task threshold for each working hour throughout the project using the historical weather data. $F(x)$ is the probability of random value X being less than or equal a specified value x. The program analyzes work stoppage based on all the variables that can potentially affect the project. For example, assuming, temperature (X), precipitation (Y) and relative humidity (Z) as the critical variables:

$$F1(x) = P(X \leq x)$$

$$F2(y) = P(Y \leq y)$$

$$F3(z) = P(Z \leq z)$$

Each distribution shows the statistics of the relevant variables for the user defined thresholds (e.g., temperatures exceeding a certain threshold). The program also determines the hourly labor productivity percentage based on Table 1 and Table 2, using historical temperature, wind speed, and relative humidity data.

RELATIVE HUMIDITY IN PERCENT (%) \ TEMPERATURE (˚ F)	-20	-10	0	10	20	30	40	50	60	70	80	90	100	110	120
90	?	55	71	82	89	93	96	98	98	96	93	84	57	0	?
80	?	57	73	84	91	95	98	100	100	98	95	87	68	15	?
70	?	59	75	86	93	97	99	100	100	99	97	90	76	50	?
60	?	60	76	87	94	98	100	100	100	100	98	93	80	57	?
50	?	61	77	88	94	98	100	100	100	100	99	94	82	60	?
40	?	62	78	88	94	98	100	100	100	100	99	94	84	63	?
30	?	62	78	88	94	98	100	100	100	100	99	93	83	62	?
20	?	62	78	88	94	98	100	100	100	100	99	93	82	61	?

Table 1: Journeymen Productivity Percentage at Various Environmental Conditions (Source: Hanna, Awad S. The Effect of Temperature on Productivity. Bethesda, MD: NECA, National Electrical Contractors Association, 2004)

Wind Speed (MPH)	Actual Temperature(°F)																	
	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	34	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	32	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-49	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-59	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-59	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-62	-68	-75	-82	-89	-97
60	24	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

Table 2: Wind Chill Factor Effective Temperature (°F) - Source: National Weather Service

The program then creates a CDF for labor productivity for each hour of the project using historical weather data. Having both labor productivity and weather information, for each hour, the program calculates the **daily effective hours** (hours the project will actually take due to delays from weather conditions) based on both work stoppage and labor productivity using:

$$DEH_j = \sum_{i=1}^{wh} EHP_{i,j} * EHTMX_{i,j} * EHTMN_{i,j} * EHRH_{i,j} * EHW_{i,j} * EHSR_{i,j} * EHSM_{i,j} * LP_{i,j}$$

where:

i: hour,

j: day,

wh: working hours per day,

DEH: daily effective hours,

EHP: effective hours due to precipitation,

EHTMX: effective hours due to maximum temperature,

EHTMN: effective hours due to minimum temperature,

EHRH: effective hours due to relative humidity,

EHW: effective hours due to wind,

EHSR: effective hours due to solar radiation,

EHSM: effective hours due to soil moisture, and

LP: is labor productivity.

The DEH (daily effective hours) equation should only include variables that can potentially affect the project. For example, if only precipitation, maximum temperature, relative humidity and labor productivity are relevant to the project, the final equation will reduce to:

$$DEH_j = \sum_{i=1}^{wh} EHP_{i,j} * EHTMX_{i,j} * EHRH_{i,j} * \; LP_{i,j}$$

where EHP, EHTMX, EHTMN, EHRH, EHW, EHSR, and EHSM are binary values, representing whether or not work will stop in a specific hour due to each variable and their thresholds at different probabilities. Put differently, for each hour, WARD System extracts the data from the past 35 years and evaluates whether work stoppage would happen (weather variables exceed the user specified thresholds). If one of the individual variable values equals zero during a specific hour in a certain year, then the entire hour will equal zero because at least one weather variable has passed the threshold (e.g., work stoppage due to extreme precipitation even though temperature condition is ideal). The program creates a CDF for each hour of the project period using the historical data. Unlike weather terms in the DEH equation, LP (labor productivity) can be any number between 0 (no productivity) and 1 (perfect productivity). Higher LP values represent higher work efficiency, and lower LP values represent lower work efficiency. If no threshold is passed during a certain hour, labor productivity due to temperature, wind, and relative humidity is the only weather factor that can delay a task for that hour.

After calculating the daily effective hours, the program computes the CDF for daily lost hours using

$$DLH_j = wh - DEH_j$$

Next, the WARD System calculates the total lost days CDF as:

$$TLD = \sum_{j=1}^{n} \frac{DLH_j}{wh}$$

where TLD is the total lost days and n is the expected task duration without accounting for weather conditions and labor productivity. The expected duration of the project can then be estimated as the initial estimates (without the weather effect) plus the total lost days because of weather-related work stoppage and labor productivity. Figure 1 provides an overview of the flowchart.

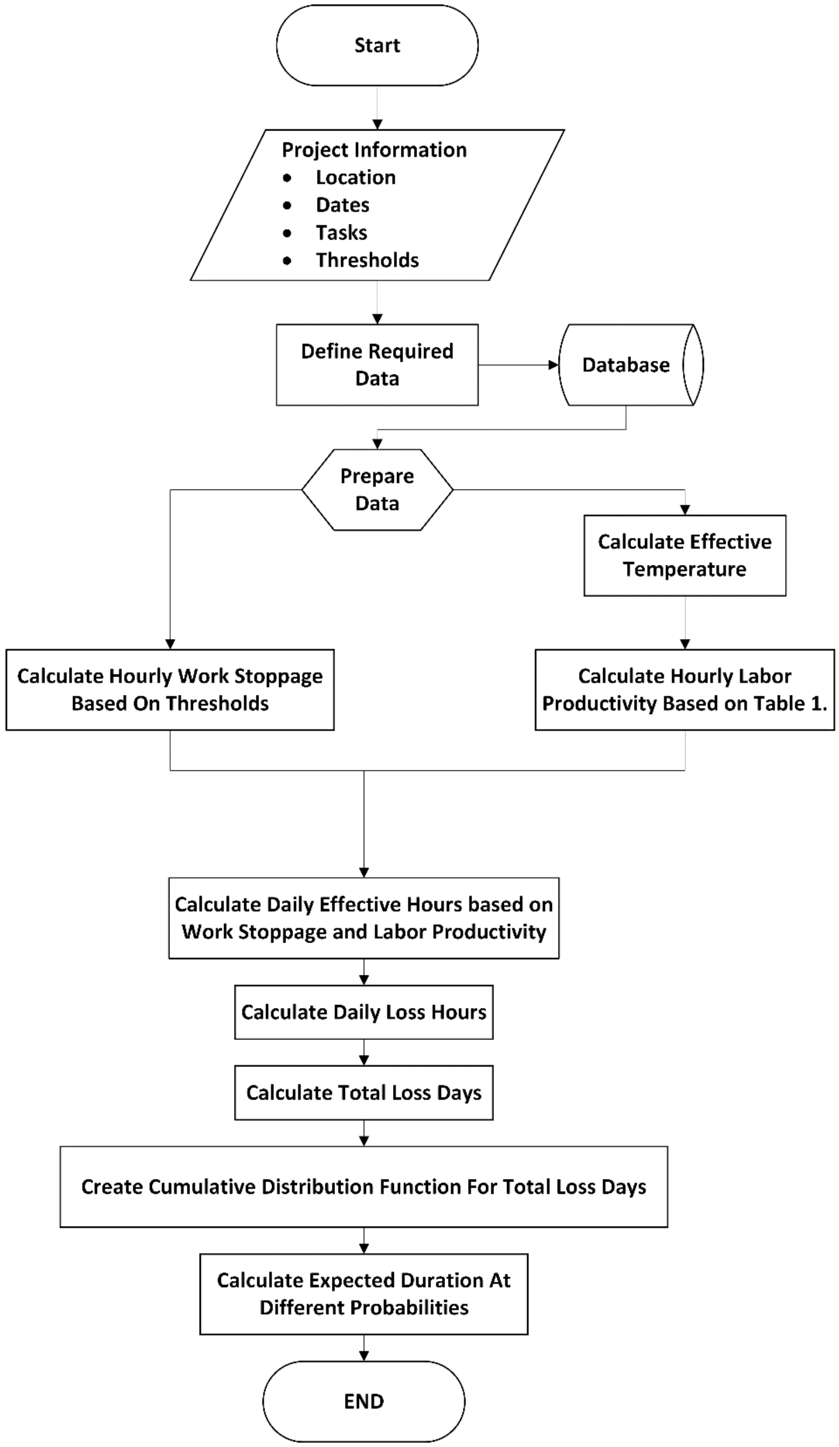

Figure 1: WARD System software flowchart

Chapter 4: Results

To provide an example for how the software works, we demonstrate application to a single short task (hereafter, Task 1) in a construction project in Washington DC. Task 1 construction is planned for January 5 to January 24 (excluding the potential weather-related impacts). We assume there is an eight hour workday, and work continues seven days a week. Figures 2 and 3 display the developed WARD System software interface for work stoppage analysis. Figure 2 shows the interface that provides general information about the project, whereas Figure 3 provides specific information for different tasks of the project (e.g., work days, start date, end date).

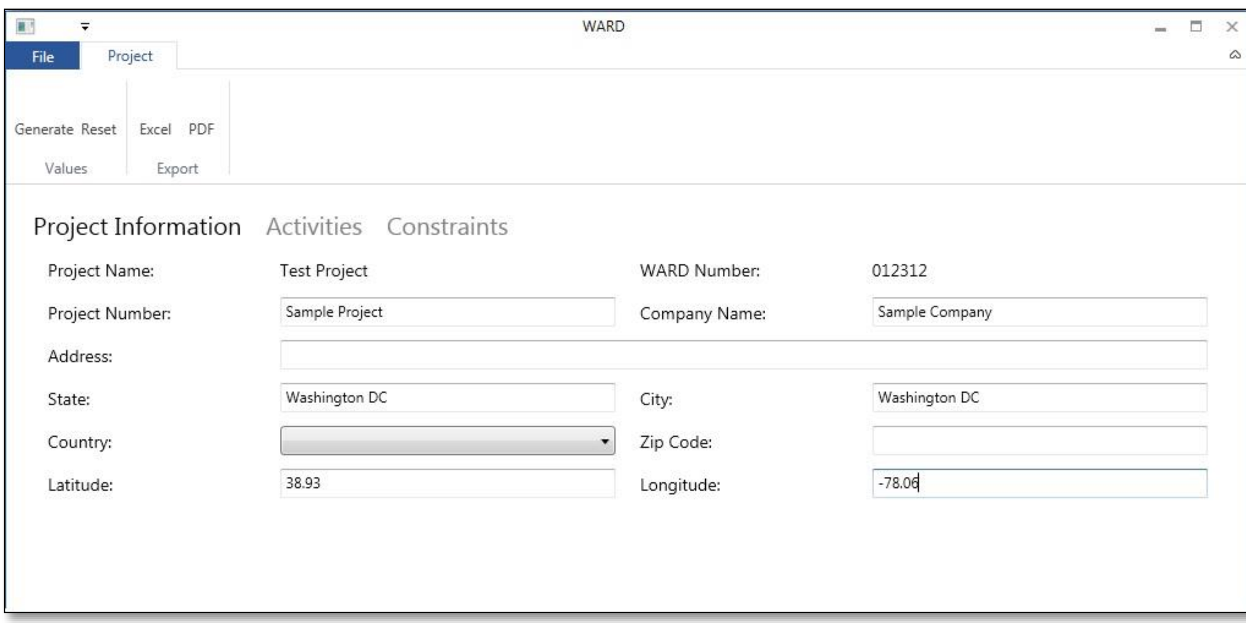

Figure 2: Project information (WARD System software interface, providing project information).

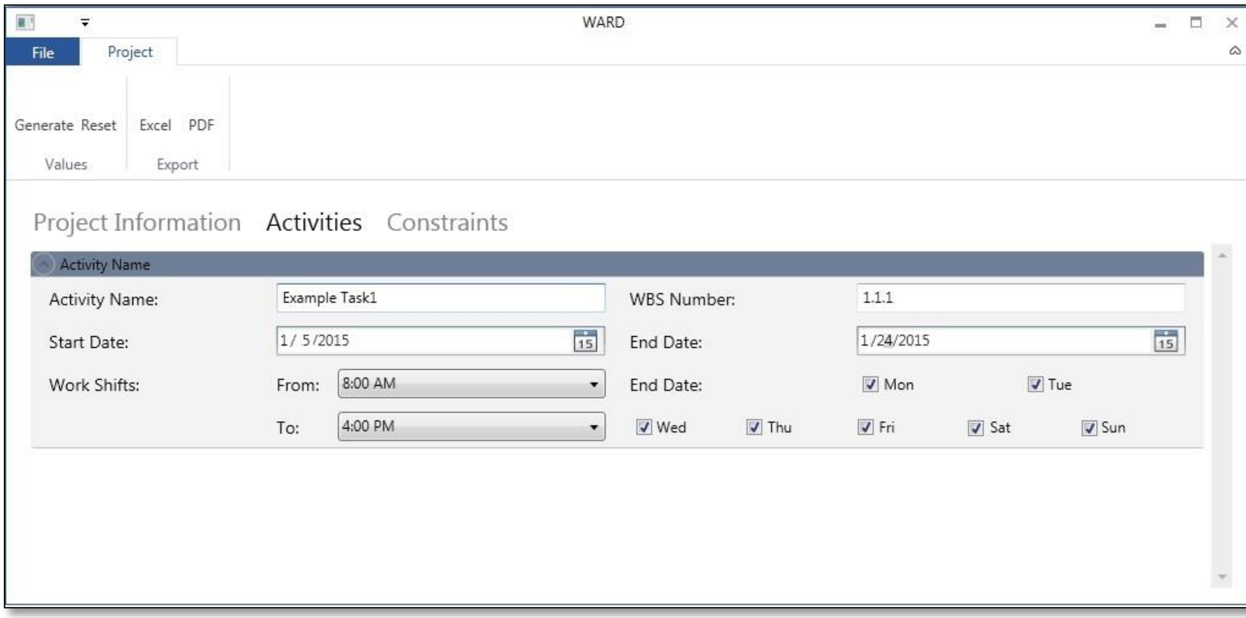

Figure 3: Task1 information (WARD System software interface, providing detailed information on project tasks).

Let us assume Task 1 is sensitive to:

- precipitation above 2 mm/day,
- maximum temperature above 100 degrees Fahrenheit,
- minimum temperature below 10 degrees Fahrenheit, and
- wind above 20 miles per hour.

Figure 4 shows the interface of the software designed for providing the user-specified thresholds. If the project is not sensitive to a variable, say solar radiation, it should be left blank.

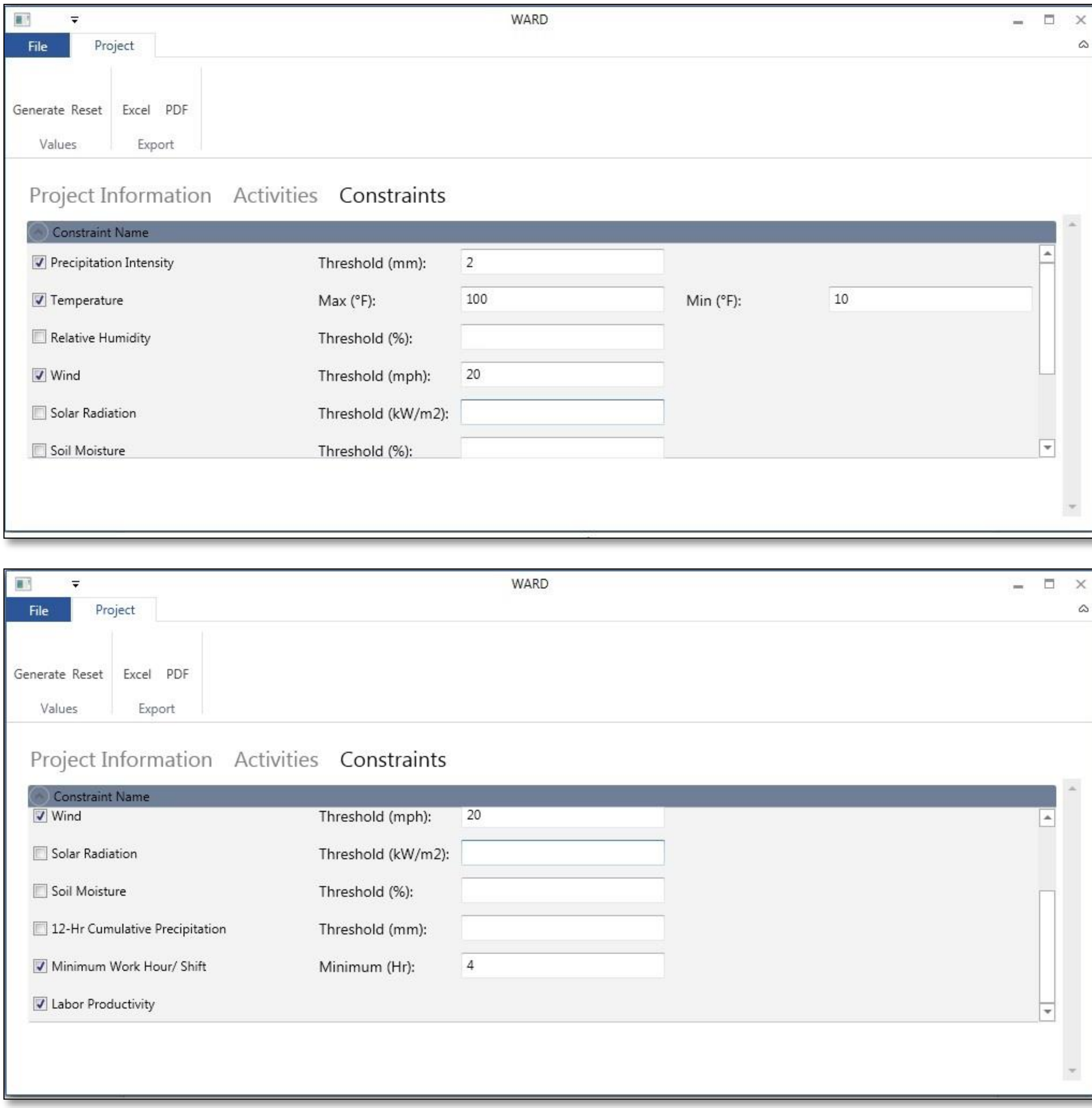

Figure 4: Thresholds for Task1 (WARD System software interface, providing project constraints)

After providing the required information, WARD System offers a CDF with estimated duration at different probabilities. This estimated duration takes into account probabilities of weather stopping work, as well as the effects of wind, temperature, and relative humidity on work efficiency. Figure 5 shows a sample output of WARD System for Task 1. Figure 5 shows that although the Total Work Days without weather interruptions is 20 days (January 5-January 24), weather interruptions can cause the task to take 22-31 days. This means that the project can take 10% to 55% longer than it would have under perfect weather conditions. Figure 5 shows that the project will take 23 days (3 extra days) or less with 25% probability, 25 days (5 extra days) or less with 50% probability, and 28 days (8 extra days) or less with 75% probability. In the worst case scenario, the 20 day task can take 31 days, which could have substantial financial costs.

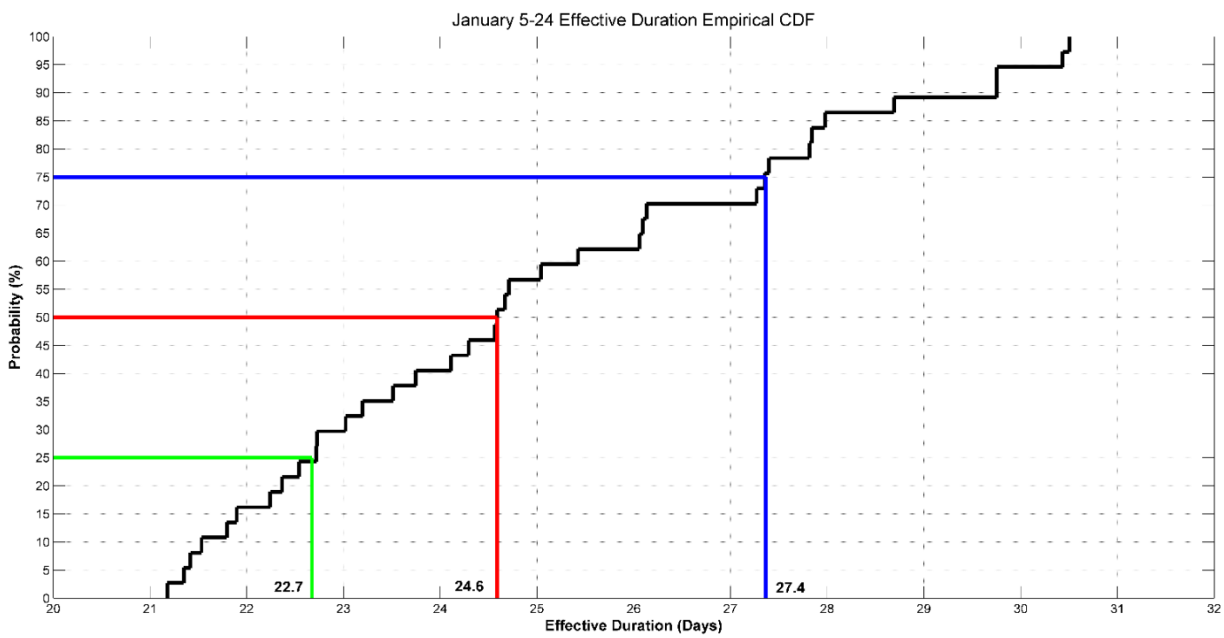

Figure 5: Effective duration for Task1 (January 5-24) considering weather-related work stoppage and labor productivity. The 20-day task is expected to take 23 days or less with 25% probability, 25 days or less with 50% probability, and 28 days or less with 75% probability.

Ward system can also give an estimate of the best time to begin a task using historical weather data, the inputted thresholds, and location. For example, if example Task 2 is located in a cold region and sensitive to cold weather, but insensitive to precipitation, the best time to start a task would be in the summer. The opposite would be true if the project is located in a hot, humid, windy location, and the project task was sensitive to high temperatures. Figure 6 shows the CDFs of effective days in each month with respect to the thresholds in Figure 4. Figure 6 shows that a task scheduled from January 1 to January 31 can take 34-41 days (3-10 extra days). However, that same task in November can take 33-38 days (3-8 extra days). Interestingly, a task occurring in August will take 37-43 days (6-12 extra days). This is likely due to labor productivity impacts (summers are hot and humid in the selected location, Washington DC). Figure 6 is just an example with a specific set of thresholds in Washington DC, and will change with location and differing thresholds.

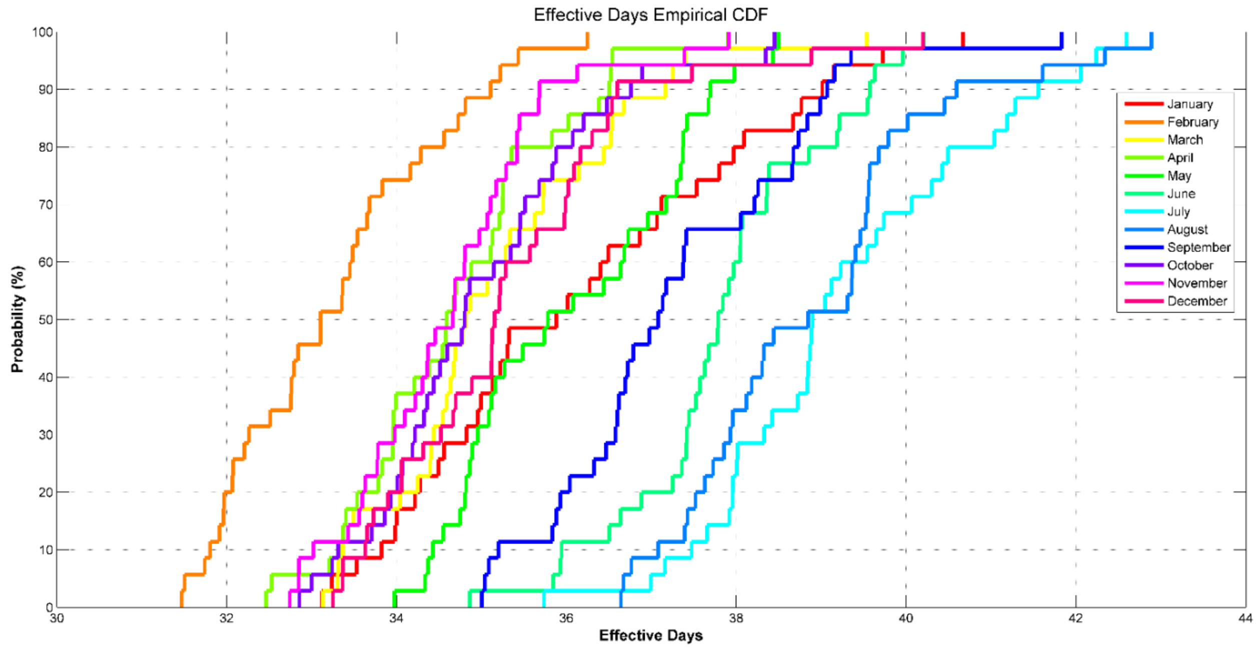

Figure 6: Effective duration for of a 1-month task for different months of the year.

Let us analyze a longer task (Task 3), with the March 1 start, and November 31 end dates without any weather delays. Again, we assume there is an eight hour workday, work continues seven days a week, and the same thresholds and location as Task 1. Without taking into account weather delays, the project will take 275 days. However, figure 7 shows the task will actually take between 316 – 334 days when considering weather delays. This means weather delays account for 15% - 19% of the approximated task duration. Figure 7 shows that the project will take 319 days (44 extra days) or less with 25% probability, 323 days (48 extra days) or less with 50% probability, and 327 days (52 extra days) or less with 75% probability.

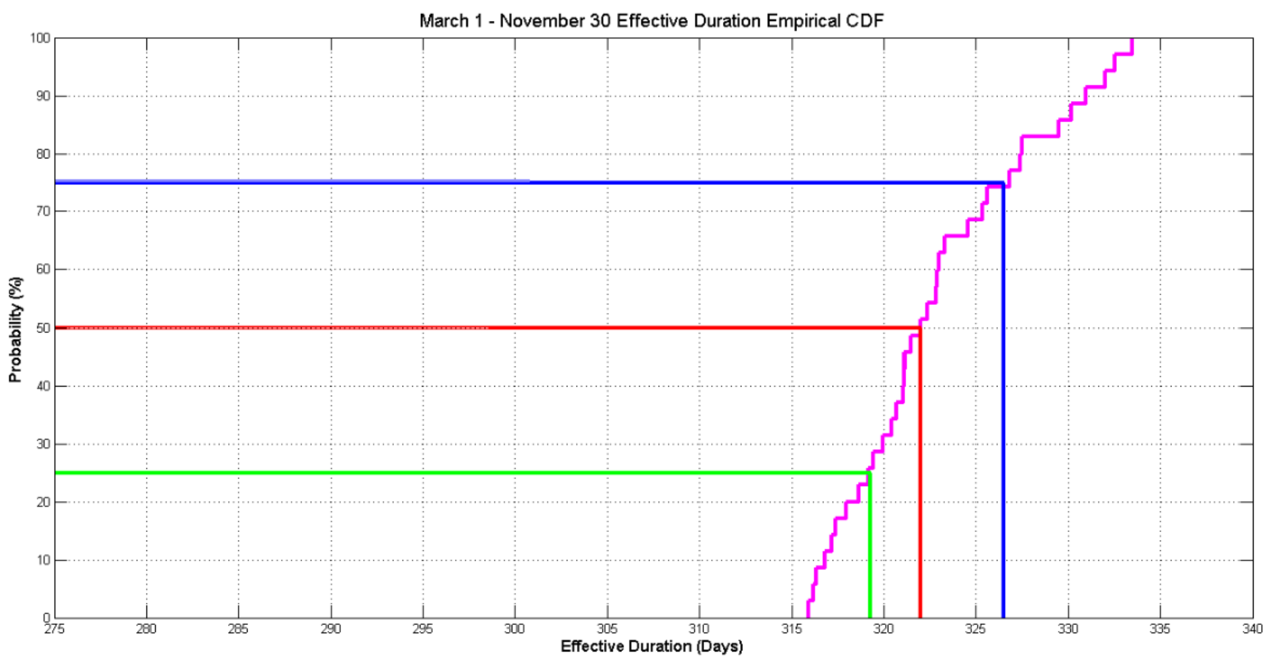

Figure 7: Effective duration for Task3. The 275-day task is expected to take 319 days or less with 25% probability, 323 days or less with 50% probability, and 327 days or less with 75% probability.

To determine the effects of work stoppage versus delay due to labor productivity, Figure 8 is created. This Figure shows Task 4's CDF, which is in the same location as Task 3, and has the same working hours as Task 3. However, Task 4 has no thresholds for work stoppage, and is only affected by labor productivity. Figure 8 shows that Task 4, which should only take 275 days actually takes anywhere between 308 – 323 days. This means that labor productivity alone adds 12% - 17% delay to Task 4.

Comparing Task 3 to Task 4 we can deduce that labor productivity accounts for 79% of the total delay, with work stoppage only accounting for 21%. It is interesting to note that labor productivity is by far the greatest factor in delays for this task. However, these CDF's, and these numbers are location and task oriented, and can greatly vary with different thresholds and locations.

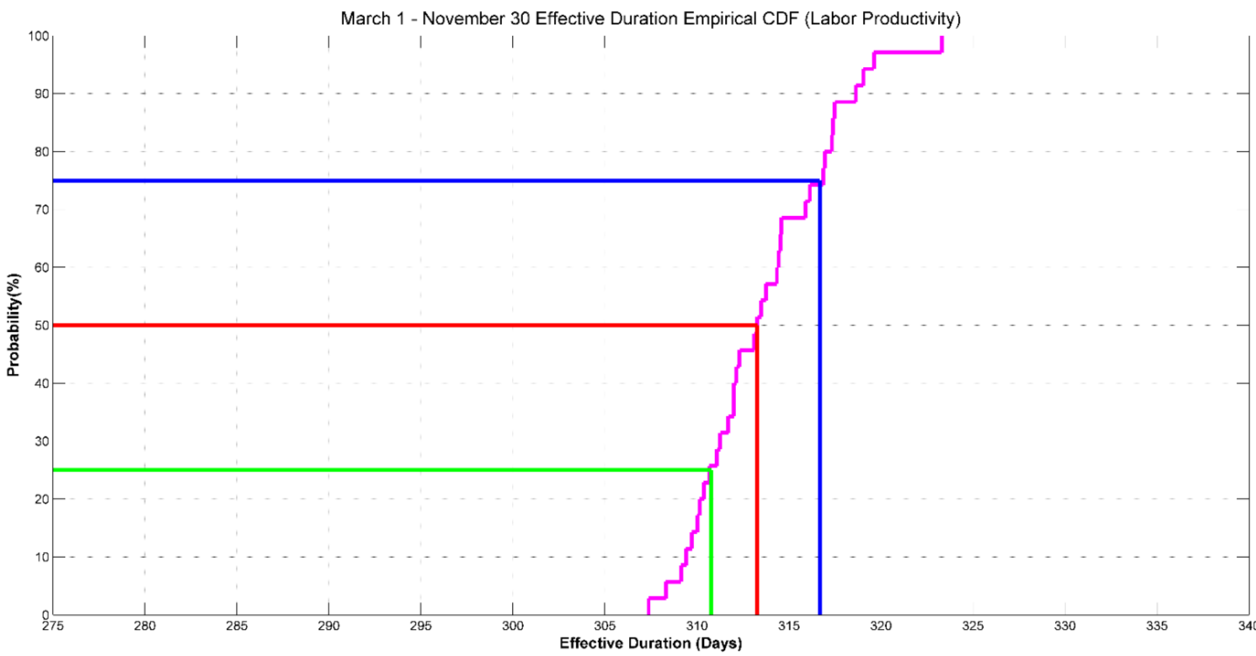

Figure 8: Effective duration for Task4 considering only the labor productivity.

Chapter 5: Conclusion

Weather conditions greatly affect every part of human daily life. Whether it is driving, working, or any other outdoor activity, weather plays some role in how we proceed. Since construction is a multi-billion dollar outdoor industry, it is important to determine and mitigate its weather risks. In this thesis, the Weather Augmented Risk Determination (WARD) System is developed, offering (a) probability of work stoppage and the estimated project length considering weather conditions; (b) information on reduced labor productivity and its impacts on project duration; and (c) probabilistic information on project timeline based on both weather-related work stoppage and labor productivity.

The WARD System uses long-term historical data to estimate weather effects on the construction activities. WARD System can analyze and determine work stoppage due to unworkable conditions and decreased labor productivity due to unfavorable weather conditions. WARD System can give important information to project managers in the construction industry to provide mitigation strategies and account for weather-related economic losses. The software (WARD System) is designed such that it can be integrated into the already available project management tools.

While the system and presented application focuses on the construction industry, the developed software is general and can be used for any application that involves labor productivity (e.g., farming) and work stoppage due to weather conditions (e.g., transportation, agriculture industry). The system is designed such that it offers work stoppage and labor productivity information based on user-defined weather conditions.

References

Adams, Richard M., et al. "The economic consequences of ENSO events for agriculture." Climate Research 13.3 (1999): 165-172.

AghaKouchak A., Cheng L., Mazdiyasni O., Farahmand A., 2014, Global Warming and Changes in Risk of Concurrent Climate Extremes: Insights from the 2014 California Drought, Geophysical Research Letters, 41, 8847-8852, doi: 10.1002/2014GL062308.

AghaKouchak A., Feldman D., Hoerling M., Huxman T., Lund J., 2015, Recognize Anthropogenic Drought, Nature, 524 (7566), 409-4011, doi:10.1038/524409a.

Allmon, Eric, et al. "US construction labor productivity trends, 1970-1998."Journal of Construction Engineering and Management 126.2 (2000): 97-104.

Altalo, M., and M. Hale. (2004, May). Turning Weather Forecasts Into Business Forecasts. Environmental Finance. 20-21.

Baldwin, J.R., Manthei, J.M., Rothbart, H., and Harris, R.B. 1971. Causes of delay in the construction industry. ASCE Journal of the Construction Division, 97(CO2): 177–187.

Ben Livneh, Eric A. Rosenberg, Chiyu Lin, Bart Nijssen, Vimal Mishra, Kostas M. Andreadis, Edwin P. Maurer, and Dennis P. Lettenmaier, “A Long-Term Hydrologically Based Dataset of Land Surface Fluxes and States for the Conterminous United States: Update and Extensions”. Journal of Climate, 26, (2013) 9384–9392.

Liang, Xu, et al. "One-dimensional statistical dynamic representation of subgrid spatial variability of precipitation in the two-layer variable infiltration capacity model." J. Geophys. Res 101.21 (1996): 403-21.

Livneh, Ben, Theodore J. Bohn, David W. Pierce, Francisco Munoz-Arriola, Bart Nijssen, Russell Vose, Daniel R. Cayan, and Levi Brekke. "A spatially comprehensive, hydrometeorological data set for Mexico, the US, and Southern Canada 1950–2013." Scientific Data 2 (2015).

Benjamin, N.B.H., and Greenwald, T.W. 1973. Simulating effects of weather on construction. ASCE Journal of the Construction Division, 99(CO1): 175–190.

Bureau of Transportation Statistics. (2011). Airline On-Time Statistics and Delay Causes: Weather's Share of Delayed Flights.

Cantwell, Frank A. A model for scheduling and analyzing construction weather delays. PENNSYLVANIA STATE UNIV UNIVERSITY PARK DEPT OF CIVIL ENGINEERING, 1987.

Changnon, S.A. (ed.). (2000). El Niño 1997-1998: The Climate Event of the Century. New York, NY: Oxford University Press, 15, 151.

Finkel, Gerald. The economics of the construction industry. Routledge, 2015.

Golian, S., O. Mazdiyasni, and A. AghaKouchak. "Trends in meteorological and agricultural droughts in Iran." Theoretical and Applied Climatology 119.3-4 (2014): 679-688.

Hanna, Awad S. The Effect of Temperature on Productivity. Bethesda, MD: NECA, National Electrical Contractors Association, 2004. Print.

Hao, Zengchao, and Amir AghaKouchak. "Multivariate standardized drought index: a parametric multi-index model." Advances in Water Resources 57 (2013): 12-18.

Hao Z., AghaKouchak A., Nakhjiri N., Farahmand A., 2014, Global Integrated Drought Monitoring and Prediction System, Scientific Data, 1:140001, 1-10, doi: 10.1038/sdata.2014.1.

Howitt, R. E., Medellin-Azuara, J., MacEwan, D., Lund, J. R. & Sumner, D. A. Economic Analysis of the 2014 Drought for California Agriculture, (University of California, Davis, 2014).

Koehn, E., and Meilhede, D. 1981. Cold weather construction costs and accidents. ASCE Journal of the Construction Division, 107(CO4): 585–595

Laufer, A., and Cohenca, D. 1990. Factors affecting construction planning outcomes. ASCE Journal of Construction Engineering and Management, 116(1): 135–156.

Lazo, Jeffrey Karl, et al. "US economic sensitivity to weather variability."Bulletin of the American Meteorological Society (2011): 709.

Maurer, E.P., A.W. Wood, J.C. Adam, D.P. Lettenmaier, and B. Nijssen, "A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States", Journal of Climate 15(22), (2002) 3237-3251.

Mazdiyasni O., AghaKouchak A., 2015, Substantial Increase in Concurrent Droughts and Heatwaves in the United States, Proceedings of the National Academy of Sciences, doi: 10.1073/pnas.1422945112.

Mehran, Ali, Omid Mazdiyasni, and Amir AghaKouchak. "A hybrid framework for assessing socioeconomic drought: Linking climate variability, local resilience, and demand." Journal of Geophysical Research: Atmospheres (2015).

Moselhi, Osama, Daji Gong, and Khaled El-Rayes. "Estimating weather impact on the duration of construction activities." Canadian Journal of Civil Engineering24.3 (1997): 359-366.

National Center for Atmospheric Research. (2011). Extreme Weathe Sourcebook: Economic and Other Societal Impacts Related to Hurricanes, Floods, Tornadoes, Lightning, and Other U.S. Weather Phenomena.

Nguyen P., Thorstensen A., Sorooshian S., Hsu K., AghaKouchak A., 2015, Flood forecasting and inundation mapping using HiResFlood-UCI and near real-time satellite precipitation data: the 2008 Iowa flood, Journal of Hydrometeorology, 16(3), 1171-1183, doi: 10.1175/JHM-D-14-0212.1.

Rojas, Eddy M., and Peerapong Aramvareekul. "Labor productivity drivers and opportunities in the construction industry." Journal of Management in Engineering 19.2 (2003): 78-82.

Smith, Gary R., and Donn E. Hancher. "Estimating precipitation impacts for scheduling." Journal of construction engineering and management 115.4 (1989): 552-566.

Shukla S., Safeeq M., AghaKouchak A., Guan K., Funk C., 2015, Temperature Impacts on the Water Year 2014 Drought in California, Geophysical Research Letters, 42, doi: 10.1002/2015GL063666.

Thomas, H. Randolph, David R. Riley, and Victor E. Sanvido. "Loss of labor productivity due to delivery methods and weather." Journal of Construction Engineering and Management (1999).

Wood, Eric F., et al. "Hydrological modeling of continental-scale basins."Annual Review of Earth and Planetary Sciences 25.1 (1997): 279-300.